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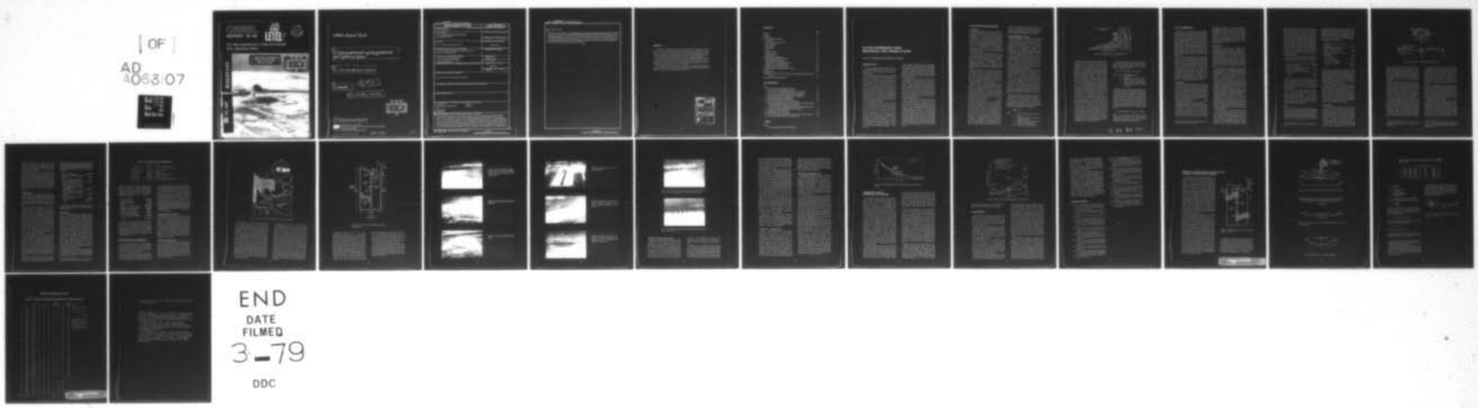

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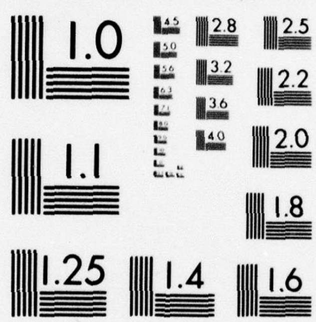
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REPORT 78-26

U.S. ARMY CORPS OF ENGINEERS

Ice fog suppression using reinforced thin chemical films

CRREL Report 78-26

(6)

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(10)

Terry T. McFadden ~~and~~ Charles M. Collins

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Ice fog suppression experiments on the Fort Wainwright Power Plant cooling pond were conducted during the winters of 1974-76. Baseline information studies occupied a sizable portion of the available ice fog weather in 1974-75. Then hexadecanol was added to the pond and dramatically improved visibility by reducing fog generated from water vapor released by the pond at –14°C. Although this temperature was not low enough to create ice fog, the cold vapor fog created was equally as devastating to visibility in the vicinity of the pond. During the winter of 1975-76, suppression tests were continued using films of hexadecanol, mixes of hexadecanol and octadecanol, and ethylene glycol monobutyl ether (EGME). Suppression effectiveness at colder temperatures was studied and limits

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to the techniques were probed. A reinforcing grid was constructed that prevented breakup of the film by wind and water currents. Lifetime tests indicated that EGME degrades much more slowly than either hexadecanol or the hexadecanol-octadecanol mix. The films were found to be very effective fog reducers at warmer temperatures but still allowed 20% to 40% of normal evaporation to occur. The vapor thus produced was sufficient to create some ice fog at lower temperatures, but this ice fog occurred less frequently and was more quickly dispersed than the thick fog that was present before application of the films.

PREFACE

This report was prepared by Dr. Terry T. McFadden, Chief, Alaskan Projects Office, U.S. Army Cold Regions Research and Engineering Laboratory, and by Charles M. Collins, Physical Scientist, also of the Alaskan Projects Office. Funding for this research was provided by the U.S. Environmental Protection Agency, Arctic Environmental Research Station, under EPA Grant DAG-D6-F642.

Merritt Mitchell and H.J. Coutts of the Arctic Environmental Research Station technically reviewed the manuscript of this report. The authors wish to express appreciation to them and to the Fort Wainwright facility engineers and power plant personnel for their assistance in this project.

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ICE FOG SUPPRESSION USING REINFORCED THIN CHEMICAL FILMS

Terry T. McFadden and Charles M. Collins

INTRODUCTION

Ice fog has plagued man since the beginning of community development in Alaska. It is a direct result of man's activities in the cold of the Alaskan winter.

Ice fog results from excess water vapor in the air which condenses and freezes, forming dense clouds of ice particles so small (8-35 μm) that they remain suspended in the atmosphere for long periods of time. Visibility restriction is an obvious danger that results from the fog, and recently the possibility of health hazards has also come to light. Many of the nuclei of the ice particles have been found to be products of combustion (Ohtake 1969), and it is feared that respiratory problems could result from inhaling such particles. In addition, the concentration of pollution products produced by adsorption on the ice particle surfaces has been the subject of some concern (Benson 1970).

Through the years, the sources of water vapor have increased. Heating of homes was the first source, introducing water vapor from combustion products into air too cold to accommodate the moisture. With the introduction of power plants the problem became more severe; products of combustion as well as cooling water discharges were combined at a single location to produce a concentrated source of ice fog. The increasing numbers of automobiles in Alaska compounded the problem still further. Today, the fog becomes a severe visibility pollutant in many areas at temperatures as high as −30°C (−22°F).

Many studies on the nature of ice fog have been conducted and much valuable information concerning its sources (Robinson 1953 and Benson 1965), its composition (Ohtake 1969) and its distribution (Benson 1970) has been obtained. Studies of ice fog nuclei (Kumai 1964 and 1966) have given additional insight into the origin and behavior of ice fog.

The extremely cold air which is conducive to the formation of ice fog is usually a result of temperature inversions which trap very stable air layers in valleys, such as the one where Fairbanks is located. The hills surrounding Fairbanks are often 10°C to 20°C warmer than the valley floor. Ice fog, once formed, accumulates progressively as long as the temperature inversion keeps the air trapped over the city. The thickness of the inversion layer increases with time, as does the density of the fog.

With the beginning of construction on the Alyeska pipeline project, a great influx of new cars into the Fairbanks area created some of the worst ice fog in memory during the winter of 1974-75. This was mitigated somewhat by the relatively mild winter of 1975-76. However, the increased population density in the Fairbanks area will remain, and every effort must be made to reduce sources of ice fog and its harmful effects on health, highway safety, and aircraft operations. This report describes an investigation of techniques for ice fog suppression at one of the major sources of ice fog in the Fairbanks area, the Fort Wainwright power plant cooling pond.

ICE FOG FROM COOLING PONDS

Evaporation

The primary purpose of a cooling pond is to dissipate waste heat from the power plant, and evaporation is one of the primary mechanisms by which heat is transferred to the atmosphere. It accounts for a major portion (on the order of 25%) of the total heat dissipated from the open water surface during the winter months. Elimination of ice fog from power plant cooling ponds could be accomplished by elimination of evaporation from these ponds. Therefore, evaporation suppression and ice fog suppression become synonymous.

When heat loss is inhibited through evaporation suppression, it must be made up by other means to avoid operating problems at the power plant. This can be accomplished by a number of methods; therefore, a knowledge of the magnitude of this heat loss is essential to the design engineer so that he may incorporate adequate alternate heat transfer modes into the system.

Since evaporation is a function of many interacting variables, mathematical predictions are difficult. This is particularly true in the microclimate around the pond, since the size of the pond creates conditions that differ from those of laboratory experiments which have been used to predict evaporation rates.

Wind is also an important parameter in the processes of the climate around the pond. Even though traditional meteorological measurements may indicate an absence of wind, the pond actually produces its own air movement, caused by the buoyancy of air which is warmed by contact with the pond surface. To replace this buoyant rising air, colder air is drawn in around the edges of the pond, produc[illegible] of air from the sides across the [illegible] towards the center. The air flow then rises to produce a plume and finally drifts away from the pond vicinity to gradually cool and settle until it rejoins the layers of air near the ground. While the air is warming, its ability to hold moisture increases, and evaporation into this relatively dry air is rapid. As the air leaves the pond surface, it begins to cool and its ability to hold moisture decreases, its vapor condenses, and formation of ice fog particles begins. The process is difficult to measure or estimate since the air movement is below the threshold of most standard meteorological wind measurement instruments and is composed of a large number of eddies and small convection cells whose direction varies constantly and randomly, making measurement of either windspeed or direction very difficult.

Relative humidity and cold air

Relative humidity is a measure of the air's ability to hold moisture; 100% relative humidity is the maximum amount of moisture that the air can hold at any temperature. Figure 1 is a low temperature psychrometric chart — a graphical display of the relationship between air temperature and the amount of water that can be held by the air at various relative humidities. It shows that air with 100% humidity at −25°C (−13°F) can hold 0.5 mg of water vapor per gram of dry air. If this air then cools to −35°C, it can only hold 0.2 mg of water vapor per gram of dry air. Therefore, warm moisture-laden air (at 100% relative humidity) leaving the pond and cooling must lose some of its moisture. This is done by condensation and the formation of ice fog particles or vapor fog droplets.

Several investigators have measured evaporation during cold weather. Yen and Landvatter (1970) conducted laboratory experiments of evaporation from water into very cold air. Ohtake (1969) reported on experiments with small 35-mm film cans during ice fog conditions in Fairbanks. Behlke and McDougal (1973) described evaporation from a pan on the top of the University of Alaska Engineering Building during the winter of 1973, and McFadden (1976) reported on evaporation from two standard Colorado pans floating in the Eielson Air Force Base power plant cooling pond during the winter of 1973.

In 1802 John Dalton proposed a formula for evaporation which has become known as Dalton's law. This formula states that evaporation is equal to some function of windspeed multiplied by the difference in vapor pressure between the water surface and the air into which the water has evaporated. It is stated as

$$E = f(u)(e_w - e_{al})$$

where E = evaporation in the unit time and area

e_{al} = water vapor pressure in air 2 m above the surface

e_w = saturation vapor pressure at temperature of water surface

$f(u)$ = a function of the windspeed.

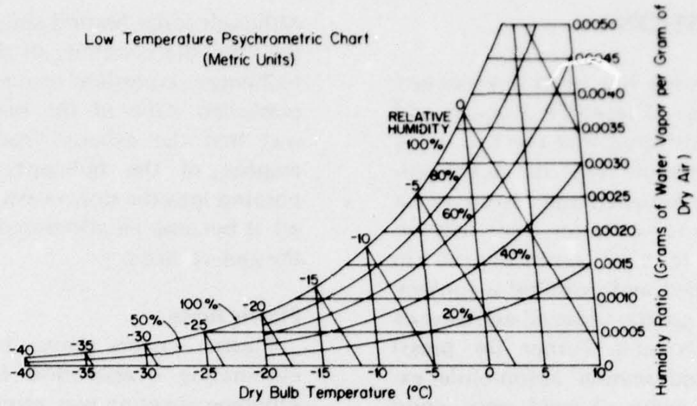

Figure 1. Low temperature psychrometric chart.

The form of the wind function is usually expressed as $f(u) = (A + Bu)$ where A and B are empirically derived constants and u the average windspeed 2 m above the surface. Many variations of this formula have been proposed. However, only Behlke and McDougal (1973), Rimshaw and Donchenko (1958), and McFadden (1976) have proposed formulas based on data taken during winter conditions in the Arctic. However, Rimshaw and Donchenko describe data taken throughout Russia at many locations so southerly that they cannot be considered arctic, and it is unclear whether the data from these sites were incorporated into their equation. During a regression analysis to derive an equation of the Dalton form from their data, Behlke and McDougal (1973) found that the wind term dropped to zero. As mentioned earlier, wind, as measured by meteorological instruments, is usually not detectable during periods of ice fog but convective air flow is nonetheless present over cooling ponds. The evaporation pan used in Behlke and McDougal's experiments was placed on top of a building, away from the microclimate of a cooling pond, and thus would not be affected by the induced air movement caused by the convective heating in the vicinity of a pond. This is a somewhat different situation than is encountered on a cooling pond itself. A pond creates its own microclimate with very low but observable air movements, even though windspeed at the local meteorological station or weather bureau is recorded as zero.

In correlating data taken at the Eielson AFB power plant cooling pond, the wind term was found to be present although small (McFadden 1976). This equation states that

$$Q_e = (13.1 + 0.132u)(e_w - e_a) \quad (\mathrm{W/m^2})$$

where Q_e = evaporative heat loss
u = windspeed
e_w = saturation water vapor pressure and water surface temperature
e_a = saturation water vapor pressure at the air temperature 2 m above the surface.

A problem arises in the use of this formula. Since wind data available to the designer are normally from weather bureau records, these data do not reflect the convective instability over the pond. A modification of this formula was made which replaces the wind term with a temperature term that reflects the driving force for convective instability. It was derived from data taken with Colorado evaporation pans on the power plant cooling pond at Eielson AFB. This formula states that

$$Q_e = [4.84 + 0.21(T_w - T_a)](e_w - e_a) \quad (\mathrm{W/m^2})$$

where T_w and T_a are the water and air temperatures, respectively. For lack of a better name, this equation has been entitled the Alaskan Winter Evaporation Equation.

ICE FOG SUPPRESSION

Elimination of ice fog has been approached along several avenues of research. Roberts and Murray (1968) demonstrated that electric fields could attract at least some types of ice fog particles. Tedrow (1969) designed and tested an exhaust gas dehydrator for a 2½-ton truck that virtually eliminated water vapor emissions, and in 1972 McKay* designed and installed a furnace dehydrator that also greatly reduced emission of water vapor. Coutts and Turner (in press) developed and tested several automobile exhaust dehydrators; some showed very good results during the winters of 1974-75 and 1975-76.

Suppression of the formation of ice fog from power plant cooling ponds was first attempted using an ice cover (McFadden 1976). The cold surface of the ice evaporated several times (as much as 10 times) more slowly than exposed areas of the warmer water that it covered. This technique proved very effective on the Eielson Air Force Base power plant cooling pond, and ice fog produced by the pond was reduced to a negligible level. However, the complexities of forming and maintaining the ice sheet over the warm (10°C to 15°C) water made the technique difficult to implement (McFadden 1976).

Air movement

Serious consideration has been given to the concept of blowing ice fog away from selected areas such as airports. For example, a suggestion was made to install large fans along the edge of the runway and thus draw air from an area free of ice fog, blowing the fog away from the runways to keep them clear for aircraft operation. However, it was shown that energy requirements for this would be excessive and [illegible]er ice fog would form around th[illegible]nt where the energy was generated (McFadden 1976).

Another variation of this proposal was the use of helicopters to hover at the top of the inversion layer. The downwash from helicopters would draw warm ice-fog-free air into the rotors and propel it downward to clear the runway. Since helicopter operations are very expensive, the costs for this technique are very high. Although some limited success was achieved in the immediate vicinity of the runway using this technique, complete results have not yet been published. One of the problems encountered was that the exhaust from the large turbine engines of the helicopters used was incorporated into the downwash, and as this air cooled, it became an additional source of ice fog in the general area.

Plastic flims

Plastic covers have been suggested for eliminating evaporation from ponds. Polyethylene sheeting was proposed by Behlke and McDougal (1973). In their experiments using a small evaporation pan, they found that evaporation, and thus ice fog, could be totally eliminated by use of the plastic film to cover the pans. But extrapolating this concept to a body of water as large as the cooling pond (over 40,000 m²) incorporates some problems of large magnitude.

A 6-mil (0.015-cm) polyethylene film large enough to cover the cooling pond area weighs in the neighborhood of 7700 kg (17,000 lb). The handling of such a film is a major construction task requiring large equipment and a carefully designed supporting structure. In order to dissipate heat from the pond, a film must float in contact with water that is moving through the cooling pond at approximately 0.113 m/min. This produces an average drag on the film of slightly under 900 N (200 lbf), which is sufficient to tear the film away from its moorings if they are not carefully designed. A thicker 10-mil film would weigh on the order of 12,700 kg (28,000 lb) and compound the handling problem still further.

Polyethylene film is very susceptible to degradation from the ultraviolet. Clear film would be good for approximately one year and would have to be replaced annually. Black film, which is slightly more stable, could possibly last three years before placement, assuming the film could be installed so that it would not be damaged by its moorings.

If the film were to tear away from its moorings, the results could be catastrophic. Should it enter the intake line to the power plant, it would stop cooling water flow to the plant and result in the shutdown of the plant within a matter of minutes. If this happened during an ice fog period, the entire Fairbanks power grid would be deprived of one of its prime producers at a time

*R. McKay, Professor of Mechanical Engineering, University of Alaska, personal communication 1968.

when power demand was very high. The ability of the other producers to make up for this loss is subject to some question, and at best would require considerable time. The clearing of the film from the intake could require a good deal of effort since the intake portion of the pond would be covered with ice and the intake submerged. Even the remote possibility of this occurrence is sufficient grounds for a veto of this technique by those responsible for operating the power plant.

Initial capital investment for the installation of a film to cover the pond is shown below. The labor for installation and sealing together of the individual 6-m (20-ft) wide sections raises the cost considerably.

The following cost estimate for covering the cooling pond with polyethylene film is based on 1977 Fairbanks prices for materials and labor:

Capital cost for polyethylene film	$10,300
Supporting structure	28,250
Labor for installation of support structure, 360-man-hours	9,000
Labor for installing the film, 200 man-hours	5,000
Total	$52,550

In addition, there would be an annual operating cost for replacement of film of $5,100 assuming a three-year lifetime for the black polyethylene. Over a 10-year period at 8% interest, this would give an annual total cost for ice fog suppression of $12,931.52/yr.

Once the film is installed covering the entire pond, ice fog suppression would be complete. However, the first snowfall — and Fairbanks averages about 125 cm (50 in.) of snow per year (Johnson and Hartman 1969) — would cover the film and soon melt, resulting in water on top of the film which would then produce ice fog and negate the function of the film.

Rafts

A variation of the film suppression technique which has been proposed to avoid the problem of water on top of the film is to construct small rafts* (Fig. 2) that have the polyethylene stretched across the top. The film then has a hole cut in the center and is weighted down so that any water falling on the surface will drain to the center and run through the hole into the pond. The costs of this type of installation are considerably higher than for the single film. For coverage of the 46,469 m^2 of pond by 5.95 m^2 rafts, 7,812 units are required. Construction costs should run as follows:

Styrofoam 2×4 in. × 9.75 m at $0.43/m	$ 4.00
Plywood structural frame 10.2 cm wide × 0.95 cm thick	7.27
Bolts — 24 × $0.15 each	3.60
Polyethylene film — 6.4 m^2 at $0.21/$m^2$	1.38
Glue and nails	0.25
Total for materials	$16.75
Labor (mass production — ½ hr/unit — at $25/hr)	$12.50
Total	$29.25

Labor for mass production of these units should require approximately ½ hr. The total cost for 7,812 units to cover the pond is $228,515, and annual replacement cost for the polyethylene is $4,182. Installation on the pond should require approximately 70 man-hours at $25/man-hour or $1,750. This gives an annual cost over a 10-year period at 8% interest of $39,980.

As discussed earlier, the primary function of the cooling pond is the transfer and dissipation of waste heat. The raft proposed above creates a dead-air space between the film and water surface which acts as an effective thermal insulator, inhibiting both radiative and convective heat transfer from the pond. This interferes severely with the cooling function of the pond, and the power plant would require additional means for dissipating its waste heat.

Injection wells

If the water necessary for operation of the power plant could be drawn from the groundwater aquifer, used to cool the condensers, and then reinjected into the aquifer, the ice fog problem associated with cooling ponds would be completely eliminated. The problems associated with this technique are, however, generally unknown and require some experimentation.

In the early 1970's, the city of Fairbanks tried a water injection well for disposal of heated water at the municipal power plant. The well

*J. McDougall and D. Carlson, personal communication, 1974.

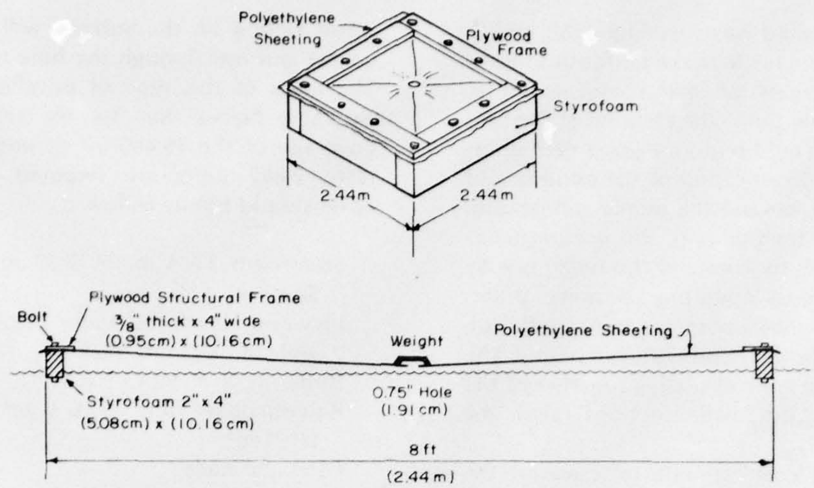

Figure 2. Cross-section of polyethylene covered raft.

was dug into the gravel on the bank of the Chena River, and water was injected into this well rather than being discharged into the river. Problems developed almost immediately due to plugging of the injection well, and the volume of water that could be forced into the well declined considerably. The well was later abandoned as unusable.*

Another problem that must be resolved is the legality of injecting water into the groundwater aquifer. Alaska's statutes specifically prohibit any contamination of the groundwater aquifers, and the aquifer in the vicinity of the Ft. Wainwright power plant is used as the primary water supply by many homes in the area. A legal opinion, which could be relatively complicated, would have to be obtained on this subject.

The above problems, however, do not appear to be insurmountable, with the possible exception of the legal problem. Groundwater injection wells have been operating for many years, and if properly constructed and operated, the plugging problem should be controllable by present technology. The condenser plugging problem may require additional manpower for condenser cleaning; however, other than the additional cost, no technical problems should be involved.

One factor that raises some problems beyond the capabilities of present technology is the low groundwater level in the aquifer during the winter months. Should the wells run dry or too low for adequate water supply, the power plant could be put into a cooling crisis. However, an emergency solution to this is to reopen the cooling pond. This would cause ice fog, of course, but would save the power plant from a shutdown.

The cost of drilling a 45-cm- (18-in.-) diam and 30-m- (100-ft-) deep hole with a perforated casing and the cost of well development come to $20,360. Assuming three such wells would be necessary for adequate backup for injection and two such wells would be necessary to provide adequate water for cooling, the total cost for the well drilling would be $101,800.

Annual operating costs of the injection wells are difficult to assess since they depend on well plugging, water quality, and pumping costs. If an additional 50-hp pump is adequate to supplement present circulating pumps and a pump and well lifetime of 10 years is used, the initial capital cost would be approximately $10,000. Pumping costs at $.041/kWh* equal $13,391/year. Increased labor required for more

*Personal communication with James Movius, Utility Manager, and other Fairbanks Municipal Utilities System engineers, 1977.

*This electric rate is the rate charged by the government to its agencies in Fairbanks (personal communication with Ken Swanson, Chief, Utilities Division, Facilities Engineers, Ft. Wainwright 1977).

frequent cleaning of condenser tubes will amount to 2 man-days per week or 832 man hours/year at $15/hour, equaling $12,480. The yearly cost for the injection well system at 8% for 10 years totals $42,532.

Despite the high cost, this is a technique that definitely warrants further investigation. The problems, both technical and social, do not appear to be insurmountable, and the predominant advantage of absolute suppression of *all* ice fog emanating from the cooling waters of the power plant is very attractive. The cost of evaluating the feasibility of the injection well technique is, however, well above the funding level of this study.

Cooling towers

Dissipation of the waste heat from the condensers could be accomplished through the use of dry cooling towers. Wet (evaporative) cooling towers could not be used, however, since they would provide an enormous water surface area which would produce immense amounts of ice fog.

Dry cooling towers, liquid to air heat exchangers where the liquid is not free to evaporate into the atmosphere, would accomplish the purpose of dissipating the unneeded heat without using the evaporative process. This technique has certain advantages over the injection well technique and has some similarities. As with the use of injection wells, it provides 100% suppression of the ice fog while dissipating the required waste heat. However, it differs from the injection well technique in that it does not rely on the continuous input of groundwater. The water used is treated and will not cause excessive corrosion or plugging of either the condenser tubes or the cooling tower.

Two main problems exist with this method. The first is the large initial cost, and the second is the possibility of a freeze-up when the system is being operated at outdoor air temperatures as cold as −65°C. An equally critical problem is that the system must be kept leak-free. Experience with this type of closed circulating system in arctic conditions does not present an encouraging record. However, this is more of an operating problem than a technological one, and no insurmountable technology gaps appear to exist.

The Rainey Corporation in Tulsa, Oklahoma, manufactures closed cooling towers which would meet the requirements for this project. A basic unit could cool the water for the Ft. Wainwright power plant to a temperature of 9°C and remove 615 kW (26,100,000 Btu/h) from the recirculated cooling fluid. The cost of this system is as follows:

Dry type cooling tower	$ 76,190
Shipping for 43,775 kg (96,300 lb)	9,600
Site preparation including concrete pad and ground work	10,500*
Piping to route the cooling water from the condensers to the cooling tower and return, including valves	22,000*
Pumps capable of circulating the water at 138 kPa (20 psi) pressure	11,000
Installation and electrical hookup of pumps	14,000*
Total	$143,290*

The total cost of this unit, amortized over a 10-year lifetime at 8% interest, yields a figure of $21,354 per year.

Chemical films

Ice fog suppression using long-chain fatty alcohols was investigated by Ohtake (Weller 1969) who found that he could not maintain the integrity of the alcohol film. McFadden (1976) confirmed this observation with experiments in 1973 at the Eielson AFB power plant cooling pond. In these experiments, it was found that even the very light breezes resulting from the cooling pond's natural convection plume and currents from the normal circulation of water were sufficient to disrupt the integrity of the film. However, McFadden (1976) also found that hexadecanol suppressed evaporation (and, therefore, ice fog) by as much as 80% in standard Colorado evaporation pans. On the basis of these studies and considerations, it was proposed to develop and test methods of reinforcing the films. This report discusses the results of such tests (see next section).

Suppression with alcohol films is an attractive option because costs for chemical application are very low. Chemicals cost less than $100.00 per application, and labor costs are less than

*Items designated with the asterisk are estimates based on 1977 Fairbanks prices. All other items are quoted prices.

Table I. Cost comparisons for ice fog suppression.

Method	*Capital cost ($)*	*Annual cost ($)*	*Probability of success*
Polythelene film cover	52,550.00	12,931.52	Very low
Polyethylene rafts	228,515.00	39,980.00	Low
Injection wells	101,800.00	42,354.00	Moderate to high
Cooling towers	143,290.00	21,354.00	High
Chemical films	47,640.00	7,998.00	High for partial suppression

$75.00 per application. No expensive initial capital investment is required, although an automated dispensing system would facilitate alcohol application. The cost for an automated dispensing system (described in Appendix A) would be as follows:

Pumps and tanks	$ 1,000.00
Controls and timers	500.00
Piping and headers	200.00
Hoops	10,000.00
Winches, 54 at $220.00 each	14,580.00
Building to house dispensers	5,000.00
Miscellaneous hardware	1,500.00
Anchors, 54 at $100.00 each	5,400.00
Cable, 12,000 ft at $.04/ft	460.00
Labor, 360 hours at $25.00/hr	9,000.00
Total	$47,640.00

Chemical costs per year amount to less than $500 and routine maintenance should not require more than 1 man-hour per week for the 16 weeks of ice fog weather, for a cost of $400. Total annual cost for 10-year life at 8% interest is $7,998.00 per year, which would be substantially lower than for any other technique, as can be seen in Table I.

REINFORCED FILM EXPERIMENTS

In order to test techniques for maintaining the integrity of chemical films for ice fog suppression, experiments were conducted during the winters of 1974-75 and 1975-76 at the Fort Wainwright power plant cooling pond.

This cooling pond is located outside the southeast corner of the Fairbanks city limits (Fig. 3). It is approximately 305 m (1050 ft) long × 150 m (500 ft) wide (Fig. 4). It is divided into unequal sections by a dike extending down the middle, leaving the two sides connected at the south end by a 15-m-wide channel. Hot water from the power plant is introduced at the north end of the western section of the pond, circulated counterclockwise around the dike and taken in again at the north end of the eastern section of the pond. The open water portion of the 45,740-m^2 (492,200-ft^2) surface produces a dense plume of ice fog (see cover) that drifts with the prevailing winds over parts of Fort Wainwright or across the Richardson Highway where several automobile accidents have been attributed to reduced visibility.

Meteorological data collection

Meteorological data were collected at the pond site by the Fort Wainwright Detachment, U.S. Army Meteorological Support Activity. Data taken included wind direction, windspeed, ambient air temperature, water temperature, relative humidity, and radiation exchange. Wind, air temperature and radiation data were taken at the dock midway along the center dike. Relative humidity was measured approximately 400 m (1350 ft) to the west of the pond and 1200 m (4000 ft) to the south. Meteorological data are tabulated in Appendix B.

Floating reinforcement grid

Previous studies have shown that the alcohol film is easily displaced by the wind (Ohtake 1969, McFadden 1976). In order to effectively suppress evaporation from a water surface with an alcohol film, it is necessary to protect the integrity of the film. A floating grid offers a means of reinforcing the film so that it will not be broken up, blown aside by the wind, or carried away by the current.

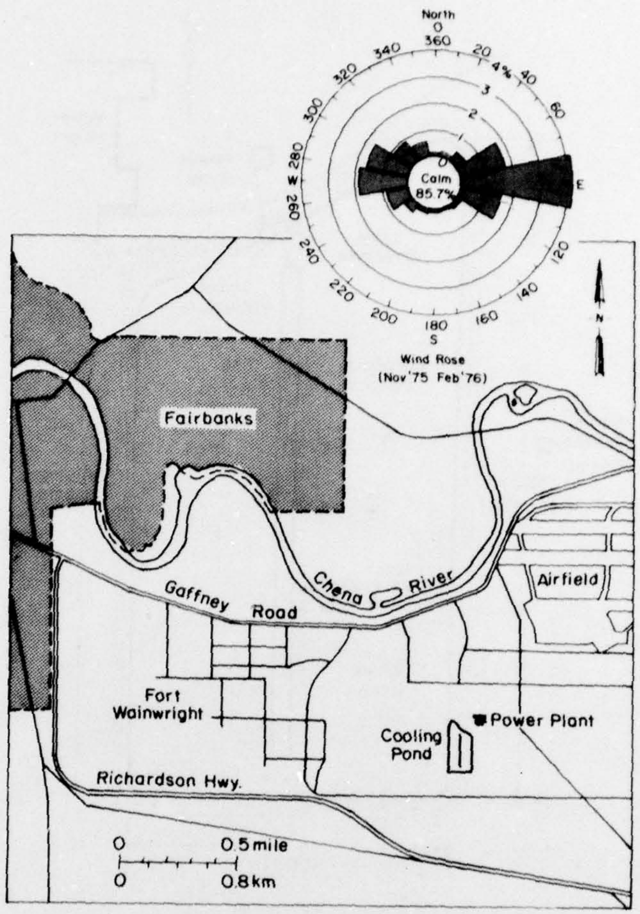

Figure 3. Location of Fort Wainwright power plant cooling pond.

Two methods were studied to establish a reinforcing grid on the surface of the pond: black 1¼-in.-diam polyethylene pipe was formed into large hoops which were floated on the pond, and in another section of the pond, floating polypropylene rope was stretched from bank to bank. The floating rope initially appeared to be an easy and inexpensive solution to the problem, as it floated high on the water and divided the surface into small discrete units. After several days, however, the rope "waterlogged." Water infiltrated between the fibers of the strands, and as a result, the rope floated so low in the water that it only occasionally broke the surface. The slightest breeze would drive ripples and alcohol film over the top, negating its effectiveness. The polyethylene hoops, on the other hand, proved to be very effective and stable, remaining afloat with sufficient freeboard even after several months on the pond.

Although more convenient, smaller hoops enclose smaller water surface areas than large hoops, and require more pipe per square meter of surface reinforced. The question therefore arises as to the optimum size hoop. Since the larger hoop diameter lowers the cost of both material and installation, maximum size was desired. However, the largest size that will still adequately support the film had to be determined. Hoops with diameters of 2.4, 4.6, 9.1 and 15.2 m (8, 15, 30 and 50 ft) were fabricated and placed on the pond. Hoops of 2.4-m (8-ft)-diam were found to be very easy to fabricate and transport; however, they required far more tubing than was available to cover the area desired for the test. Hoops with diameters of 9 m (30 ft) and larger, on the other hand, were found to have poor shape stability while floating on the pond and would not give adequate support to the film.

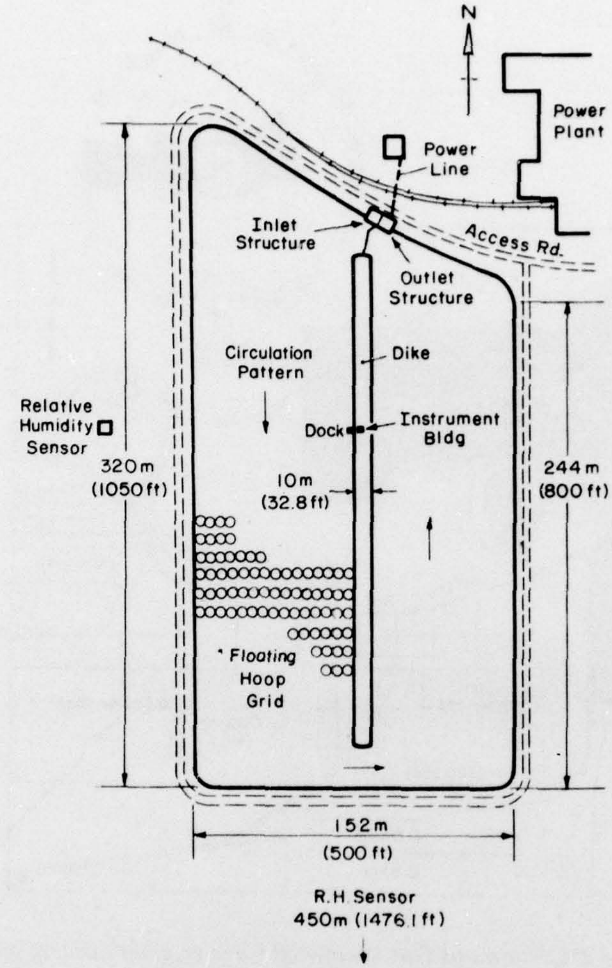

Figure 4. Layout of Fort Wainwright power plant cooling pond.

Difficulties caused by the cold of late November in Alaska made necessary to fabricate the hoops indoors and then transport them to the pond for installation. The 2.4-m (8-ft)-diam hoops were found to be the largest practical size that was transportable during the cold without specialized hauling equipment. During warm weather, when the plastic pipe was more flexible, larger diameters could be transported because the hoops could be deformed into ellipses without cracking or taking a permanent set. The 4.6-m (15-ft)-diam hoops were then preferable due to economic considerations.

Once the hoops were fabricated and transported to the pond, they were fastened together in long chains, stretched across the surface, and secured on each side. It was not necessary to connect adjacent chains and it was possible to leave up to 3-m (10-ft) spaces between adjacent rows of hoops. Figure 5 shows the rows of hoops installed on the pond.

Alcohol was spread on the water surface inside the different size hoops, and it was found that after a period of several hours the film was established and would maintain itself in the 4.6-m (15-ft)-diam hoops. Applying alcohol during windy periods required a longer time for the establishment phase.

Figure 5. Rows of 8-ft-diam hoops installed on the cooling pond. Weather at this time was not conducive to ice fog formation.

Figure 6. Pond before application at 0820 hours.

Figure 7. Overall fog reduction at 0910 hours.

Figure 8. Large areas with little or no fog at 0920 hours.

Figure 9. Large clear area upstream of hoops and along west edge of pond prior to applying hexadecanol to the hoops.

Figure 10. Alcohol film layers accumulating at the leading edge of the hoops, just prior to applying hexadecanol to hoop area.

Figure 11. Pond 24 hours after application. Note that the film is still actively suppressing the fog in the area of the hoops.

Figure 12. Pond 48 hours after application. Film still is intact in the area of the hoops.

Application of the hexadecanol film

Sufficient baseline data had been collected by mid-February 1975 to begin experimental application of the hexadecanol film. It was desirable to apply the film on a calm, cold day of −30°C or colder when ice fog would be present, but no such day occurred during the remainder of February and into March. Therefore, a calm day at −14°C was finally selected even though only vapor fog was present. Except for the relatively warm temperature, atmospheric conditions were favorable for an experimental application of hexadecanol on Tuesday, 4 March. Winds were calm, and the sky was overcast.

Hexadecanol in a granular form was applied to the pond from a small boat starting at 0820 hours. The boat traversed from the warm to the cool side of the pond spreading approximately 9 kg (20 lb) of chemical to the warm side and approximately 3.5 kg (18 lb) to the cool side. Finally, hexadecanol was applied to the areas within

the film reinforcing hoops. Specific proportioning was not attempted; the only consideration being to ensure that each section of the pond received alcohol well in excess of that required for a monomolecular layer. The total time for application was 20 minutes.

Photographic coverage was obtained from several vantage points to record the appearance of the fog before, during, and after application. Photos taken from a circling helicopter afforded the clearest perspective of the changes in the fog. An overall reduction in the fog is clearly apparent in the aerial photos (Fig. 6-8). Furthermore, Figures 9 and 10 show a remarkable local contrast in the fog. Large areas of the pond show little if any fog, while immediately adjacent are thick walls of fog marking the edge of the film.

From the ground the film was observed to be swept slowly downstream by the surface current. After approximately an hour, the hexadecanol was found concentrated in layers against the band of hoops midway down the warm side, and against a surface dam separating the two sections of the pond. Fog was absent approximately 25 m (80 ft) upstream of the surface dam where the hexadecanol film tapered from thick scum at the dam's edge to a monomolecular layer film upstream (Fig. 11 and 12). Alcohol was also found clinging to some edges of the pond where it was calmer.

Atmospheric conditions were constant throughout the hour of photographic coverage (0820 to 0920). Winds remained calm; the sun remained shaded by heavy clouds, and the air temperature rose only 1°C. The hexadecanol, therefore, appeared to be the only variable responsible for the fog suppression.

Hexadecanol, octadecanol mixes

There is some evidence that longer chain alcohols are more effective than hexadecanol in suppressing evaporation (Dressler 1969). However, the longer chain alcohols come at a much higher price. Some evidence exists to indicate that mixes of the different alcohols provide even greater suppression ability (Noe and Dressler 1969). In an effort to test this theory, a supply of octadecanol ($C_{18}H_{37}OH$) was obtained and mixed with the hexadecanol ($C_{16}H_{33}OH$). The mixture was 20% octadecanol and 80% hexadecanol. Neither superior performance nor superior lifetime could be confirmed with the use of this mix when compared to hexadecanol alone. However, due to equipment failure, it was impossible to make any quantitative measurements using either the transmissometer or high volume sampler. Clearly more work needs to be done in this area to confirm or dispute any improved suppression performance of alcohol mixes under ice fog conditions.

Ethylene glycol monobutyl ether

A chemical marketed by Shell Oil Company with the trade name, "Oil Herder," was investigated for its fog suppression capability. It is primarily used on water for concentrating oil spills into a small area where they can be easily handled. The chemical is ethylene glycol monobutyl ether (EGME), a clear liquid that has a high spread pressure and low vapor pressure. According to the Shell Oil Company research brochure, it is nontoxic both to humans and fish and is biodegradable.

The chemical was applied to a cooling pond at the Eielson AFB power plant and the suppression effectiveness monitored during the winter. Several rows of floating hoops were placed on the pond, but their presence did not appear to be as important to film integrity as when the long chain alcohols were used. It is difficult to assess the precise suppression effectiveness of EGME due to the lack of funds or time for comprehensive tests; however, laboratory tests indicate that it suppresses approximately 60% of the evaporation from an open water surface as compared to hexadecanol suppression effectiveness of as high as 85%. Its increased spread pressure helps it to resist tears in the film and gives it a longer lifetime, a distinct advantage over hexadecanol. During the months while the film was on the Eielson cooling pond, no adverse affects to the pond, the power plant, or any of its operations were observed. The suppression effectiveness appeared to be good. No quantitative measurements were possible; however, it was apparent that the pond was not a major ice fog contributor while EGME was on the pond, whereas the stacks from the power plant still contributed significantly. In many instances visibility across the pond was unrestricted while ice fog covered the rest of the base. Although its cost is several times as high as that of hexadecanol, one application of EGME appeared to be adequate for the entire ice fog season, making it economically competitive.

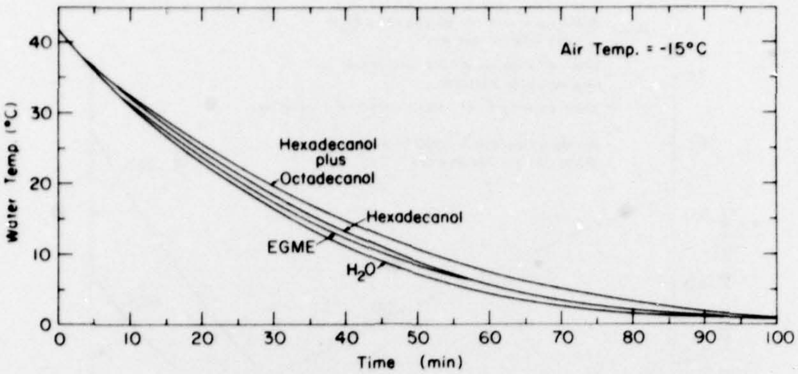

Figure 13. Effect of chemical films on heat transfer rate from water surfaces.

LABORATORY TESTS OF SUPPRESSION EFFECTIVENESS

A test was devised to measure the ability of various films to suppress the evaporation component of heat lost from a water surface. The basis of the test is the assumption that evaporative heat loss is a good quantitative measure of evaporation. The procedure is to place pans of water covered with various films in a coldroom at varying temperatures. The pans are insulated on all sides, leaving only the surface of the water exposed to the cold of the room. Heat loss, as the pan cools, is then limited to losses from the water surface: radiation, convection, and evaporation. The convective and radiative losses should be equal. The only difference in the cooling rate of the pans will be that of the evaporative cooling losses due to the difference in suppression effects of various chemicals on the surface. In this manner, the evaporation suppression by various chemicals can be compared to the control pan (water without chemicals). Figure 13 shows the results of some of these tests. Using this technique, it can be seen that hexadecanol is more effective than EGME, and that mixtures of hexadecanol and octadecanol are somewhat better than the hexadecanol alone.

In order to combine the qualities of long life and higher spread pressure of EGME with the better suppression inhibiting qualities of hexadecanol, a mixture of EGME and hexadecanol was tested. However, the suppression qualities tended to be very close to that of EGME alone. This may be caused by the higher spread pressure of the EGME, separating the molecules of hexadecanol and resulting in EGME as the only cover over most of the water surface. The immiscibility of hexadecanol in EGME may also be a factor. It has not yet been determined whether hexadecanol will establish a film in the presence of EGME. Further studies on this particular subject and more tests are clearly needed.

Figure 14 shows the effects of varying degrees of water vapor suppression. For example, 3.47 g/m² min of water vapor would be produced from an open water surface at −20°C (point A). However, air entering the pond area at 50% relative humidity and leaving saturated would be capable of absorbing only 0.95 g/m² min (point B) leaving 2.52 g/m² min of excess vapor to form fog. If 80% suppression is achieved, only 0.6 g/m² min would be produced (point C). Therefore, no excess vapor would be available to produce ice fog. If only 60% suppression is achieved, then 1.3 g/m² min is produced (point D) and 0.35 g/m²-min of this is excess and will produce fog (D-B). However, compared to the 2.52 g/m² min of fog arising in the case of no suppression, it is apparent that much less of the local area will be affected for considerably less time.

Figure 14 also shows that if 80% suppression is achieved, fog will not form until −23°C (−9°F), whereas without suppression fog will form at −10°C (14°F). U.S. Weather Bureau records show that Fairbanks experiences an average of 145 days during which the mean temperature falls below −10°C. However, there are only 80 days of −29°C (−20°F) or colder.

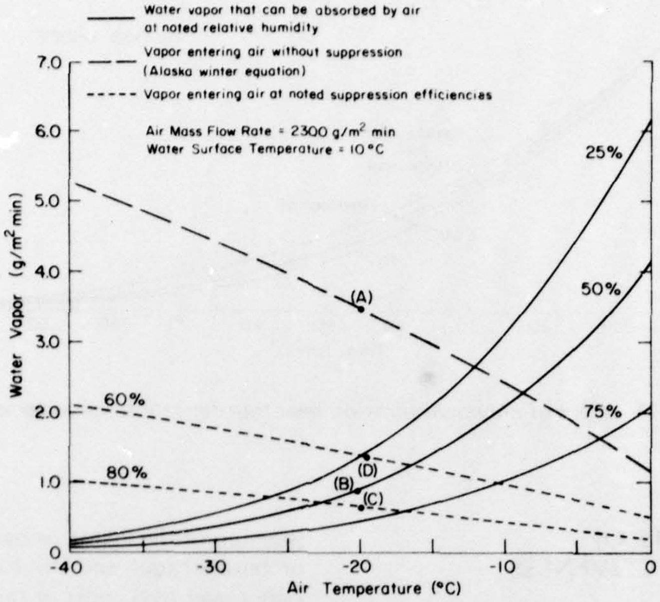

Figure 14. Excess water vapor (fog) produced vs temperature.

Therefore, the suppression effort results in 65 fog-free days or 44.8% fewer days of fog.

CONCLUSIONS

The dramatic improvement in visibility from reduction of fog after application of hexadecanol suggests that this technique may be very useful for economic reduction of cooling pond contributions to the overall ice fog blanket of the Fairbanks area.

Chemical films are clearly the most economically attractive method. Although they only partially suppress fog, the cost of 100% suppression is 267% higher for the cooling tower approach and 532% higher for the injection well technique. No other techniques discussed would yield 100% suppression.

The performance of a grid to reinforce the film was very satisfactory and appeared to function much as predicted. It is felt that the problem of maintaining the film integrity has been satisfactorily solved for light winds and water currents. Stronger winds (that might overcome the effect of the reinforcing hoops) would probably dissipate the ice fog anyway.

The rapid bacterial degradation of the hexadecanol and octadecanol films presents a problem which must be approached using one of several techniques. Treating the film to destroy the bacteria without harm to other ecological systems may suffice. Another alternative would be to use films which are not so readily biodegradable, for example, ethylene glycol monobutyl ether. This film has been shown to be harmless to marine life (Shell Oil Co. 1974) and it is also biodegradable, but at a much lower rate than hexadecanol. Other advantages include a much higher film spread pressure and a liquid state at normal temperatures. It is immiscible in water and practically invisible. Suppression effectiveness of EGME is lower than that of hexadecanol, but its longer life and higher spread pressure are compensating factors. One application per season is sufficient, and a viable film cover still appears to be intact at the end of the winter.

Further research is needed to identify other chemicals which will suppress evaporation and perhaps even surpass the effectiveness of those investigated in this report. It is apparent that much of the visibility problem can be alleviated with films at a very reasonable cost. But it must be realized that chemical films that provide only partial suppression (up to 80%) will still allow some ice fog to leave the pond. Since visibility in the immediate vicinity of the source is an inverse exponential function of ice fog density, it quickly drops to near zero with only a small amount

of ice fog present. Although little advantage of the suppression activity can be seen in the immediate vicinity of the source, the dispersion of fog as it moves away from the source allows visibility to improve within a few hundred meters, whereas without the suppression effort a much larger area is affected.

Eliminating all of the fog produced by the pond will be extremely expensive and require one of the other techniques mentioned — or perhaps a method yet unknown. Therefore, the economic cost of ice fog should be determined to compare the cost of suppression with the cost of living with ice fog. Although the fog is present only during a small portion of the year, its cost can be high due to lost revenue from flights that cannot land, repair of vehicles involved in accidents caused by fog, and the possible loss of human life from accidents or health-oriented problems. These economic factors clearly need to be investigated and considered.

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APPENDIX A. DESIGN FOR AN AUTOMATIC THIN CHEMICAL FILM APPLICATION SYSTEM

The application of a thin chemical film to the pond can be done by a number of methods. An automatic system would consist of the following devices: a slurry tank with mixing impeller capable of mixing $0.21\ m^3$ (55 gal.) of water and chemical slurry. (In the case of EGME the chemical is applied in its natural liquid form.) The tank is connected to a header which extends across the upstream end of the pond. The header should be 49 m (150 ft) wide and have holes every 5 m (15 ft) (Fig. A1). A pump capable of delivering approximately $1.5 \times 10^{-5}\ m^3/s$ (¼ gpm) to the header is needed. The header should be supported on the pond by floats so that it stays at the water level of the pond. This will keep it in contact with the pond level. A common industrial timer should be used to activate the system once every four days. Each time $0.076\ m^3$ (20 gal.) of slurry and/or chemical should be pumped out into the pond.

Each chain of floating hoops across the width of the pond should be connected to a ¼-in.-diam steel cable [breaking strength of at least 17 kN (4000 lbf)]. The cable will extend from an anchor across the pond around a pulley and back across the pond to a hoist capable of lifting 1,130 kg (2500 lb) (Figs. A1 and A2). When the hoist is activated, it will draw the cable to a tension of approximately 11.1 kN (2500 lbf) which will lift the cable and the attached hoops above the pond (Fig. A3). Floats attached to the cable will keep it floating at the surface during the relaxed periods to assure that it it does not sink any of the hoops. The hoops will be attached to the cable by a sliding mechanism so that they may slide along the cable as it is drawn up (Fig. A4). This will raise the hoops off the water surface and allow the film to pass by. After the film front has passed and spread over the area below the hoops, the hoops will be lowered, entrapping the film within their confines and establishing a cover over the entire pond.

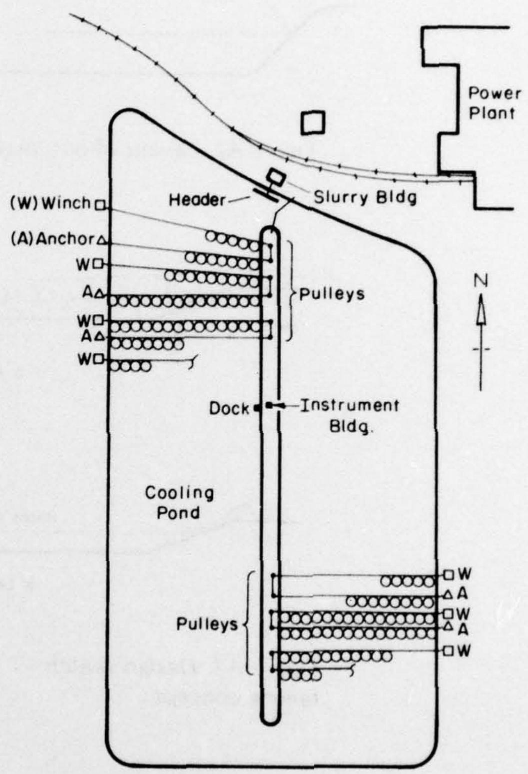

Figure A1. Design sketch of chemical application system — plan view.

Timing of the raising and lowering of the hoop chains will have to be done during installation of the application system. The timing will be set to raise the hoops so that the film will be allowed to spread and to lower them before the film has completely passed. Once set, this time should not change. Calculations for the design of the raising and lowering device are given below.

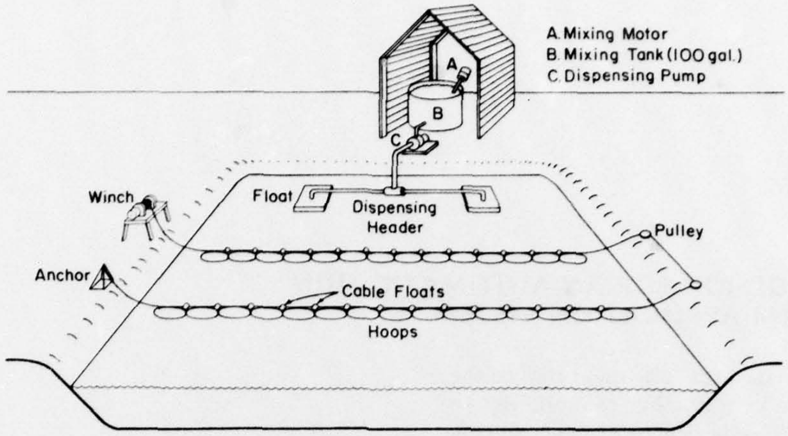

Figure A2. Layout of automatic chemical film dispensing system.

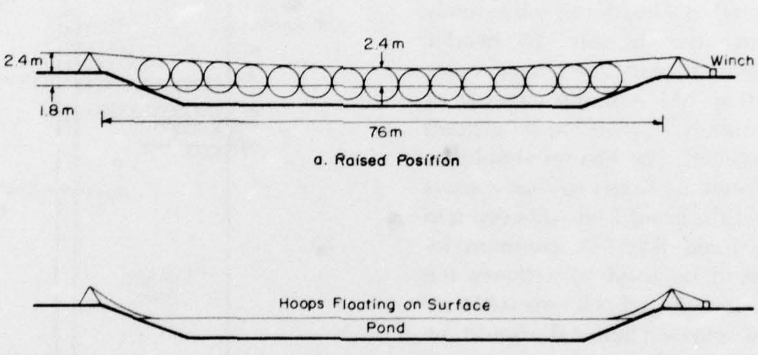

Figure A3. Design sketch — chemical application system — hoop raising concept.

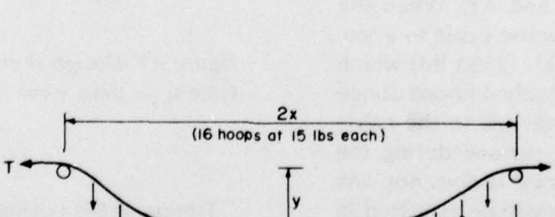

Figure A4. Catenary arc calculation parameters.

Table AI. Cable tension (lbf) vs deflection for one span (Marks 1951, p. 2-57).

y	y/x	Z	wx/T	Cable/Cable & hoops		s/x	s
2	0.0148	0.0296	0.0296	456	4679	1.00015	135.0
4	0.0296	0.0592	0.0593	228	2335	1.00059	135.1
6	0.0444	0.0888	0.0889	152	1558	1.00132	135.2
8	0.0593	0.1185	0.1167	116	1187	1.00272	135.4
10	0.0741	0.1480	0.1464	92	946	1.00365	135.5
15	0.1111	0.2213	0.2160	62	641	1.00818	136.1
20	0.1481	0.2940	0.2817	48	492	1.01447	137.0

Let: w = weight/ft
y = ft
$2X = 270$ ft ($X = 135$ ft)
T = tension (lbf)
Z = auxiliary variable
$2S$ = length of the arc

for: ¼-in. cable (breaking strength >4000 lbf)
$w = 0.1$ lb/ft for cable + 0.92 for hoops
$= 1.02$
$wx = 138.5$ lb

If a catenary (Table AI) is such that it touches the water surface at $y = 20$ ft and then is further relaxed until the line lies on the water (Fig. A5), the total relaxed length is

$$L_v = (28 + 135 - 20) \times 2 = 286$$

The stretched length when the center of the cable arc is 10 ft above the surface is

$$L_s = 135.5 \times 2 = 271.$$

Then $\Delta L = 286 - 271 = 15$ ft/arc.

For a motor pulley to raise two spans of hoops would require a takeup capacity of $15 \times 2 = 30$ ft.

Hoops would have to be free to slide along the cable during the takeup process to avoid entangling them in the pulleys (Fig. A4).

Electric winch units capable of exerting a tension of 8416 N (1892 lbf) are required to lift the center of each catenary 3.3 m (10 ft) above the surface; ¼-in. steel cable should give an adequate safety factor.

Although a lift of 3.3 m (10 ft) will not raise the centermost hoop completely from the water, it will be sufficient to allow the hexadecanol or EGME to flow into the hoop area and be captured when the hoops are lowered. One winch could then handle two spans.

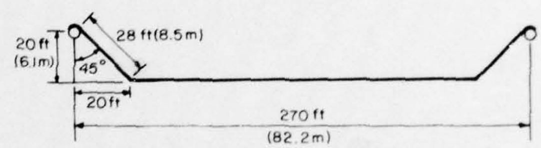

Figure A5. Calculation for arc hitting water surface at $y = 20$.

APPENDIX B. METEOROLOGICAL DATA.

Table BI. Ft. Wainwright cooling pond meteorological data, 3 February-6 March 1976.

Date	Time	Ta_1/Ta_2 (°C)	Tw_1 (°C)	Tw_2 (°C)	Tw_3 (°C)	Average windspeed (mph)	Average windspeed (m/s)	Wind dir	RH ¼ mi upwind (%)	Remarks
3 Feb	0830	−22/−24	14	14	12			W	57	Accuracy probably no better
	1145	*m/−22				2.5	1.1	SE	69	than ±1°C
	1600	−17/−21	13	13	14	1.9	0.8	NE	75	
4 Feb	0830	m/−21	16	16	16			SE	m	Ta_1 = Air temp over pond
	1145	m/−23				2.3	1.0	SW	73	
	1515	−19/−22	14	14	14	2.1	0.9	NE	48	
5 Feb	0815	m/−26	14	14	12			N	10	Ta_2 = Air temp ¼ mile upstream
	1130	m/−23				2.1	0.9	N	36	
	1545	m/−20	15	15	15	1.9	0.8	NN	59	
6 Feb	0815	m/−26	16	15	15			N	60	Tw_1 = Water temp 2 cm below
	1130	m/−19				1.9	0.8	N	63	surface ≅100 m downstream
	1600	m/−17	19	18	18	2.4	1.1	NN	64	from inlet
7 Feb	0815	m/−21	16	16	16			E	64	Tw_2 = Water temp 2 cm below
	1230	m −19				1.9	0.8	E	71	surface ≅200 m downstream
	1545	m/−19	18	19	18	2.5	1.1	NW	74	from inlet
10 Feb	0830	m/−29	18	17	16			NE	m	Tw_3 = Water temp 2 cm below
	1130	−19/−19				3.2	1.4	E	10	surface ≅300 m downstream
	1545	−19/−20	18	17	16	3.8	1.7	E	10	from inlet
11 Feb	0830	−24/−29	17	16	16			NE	27	
	1130	−25/−26				2.4	1.1	SE	42	
	1545	m/−26	17	16	16			NE	39	
12 Feb	0830	−23/−29	17	16	16			NE	39	
	1130	−22/−23				4.6	2.1	NE	10.	
	1545	−23/−25	17	17	16	5.7	2.5	E	26	
13 Feb	0830	−28/−30	16	15	15			E	49	
	1130	−24/−25				7.1	3.2	E	53	
	1615	−26/−28	15	15	14	6.3	2.8	E	24	
14 Feb	0830	−28/−32	13	12	12			E	24	
	1145	−25/−28				3.4	1.5	NE	23	
	1545	−25/−22	14	14	13	1.9	0.8	E	63.	
15 Feb	0830	−25/−27		15				NE	59	
	1145	−22/−25				3.3	1.5	SW	10	
18 Feb	0830	−12/−12	18	17	16			S	80	
	1130	−12/−13				5.3	2.4	S	23	
	1600	−14/−14	18	17	17	3.3	1.5	W	72	
19 Feb	0845	−19/−20	18	16				W	71	
	1145	−18/−20				6.1	2.7	W	72	
	1600	−19/−17	16	15	15	3.4	1.5	SE	65	
20 Feb	0830	−29/−31	17	17	16			E	33	
	1130	−25/−25				14.3	6.4	E	55	
	1530	−22/−23	17	17	17	4.5	2.0	E	50	
21 Feb	0830	−8/−6	19	18	17			NE	60	
	1130	−3/−3				6.7	3.0	E	·43	
	1530	−1/−2	19	18	18	5.1	2.3	E	88	
24 Feb	0830	−19/−20	18	18	18			E	23	
	1130	−13/−15				2.4	1.1	E	75	
	1530	−6/−10	20	19	19	1.4	0.6	E	74	
25 Feb	0830	+1.2/−4.2	20	20	20			E	93	
	1130	+3.3/+0.3				5.3	2.4		83	
	1530	+3.1/+0.2	20	20	20	1.1	0.5	E	82	
26 Feb	0830	+1.1/−2.8	20	19	19			E	82	
	1130	+1.3/−1.9				1.8	0.8	E	76	
	1545	+5.0/+2.1	21	20	20	2.7	1.2	E	65	
27 Feb	0830	−2.8/−2.1	20	20	20			S	88	
	1130	+0.1/+0.3				3.1	1.4	SE	89	
	1530	+3.9/+3.8	21	21	20	2.4	1.1	E	86	
28 Feb	0830	−13.9/−14.2	19	19	19			SE	10	
	1130	−3.9								
	1530	0	19	19	19					
3 Mar	0830	−13.2/−9.5	17	16	15			NE	75	
	1130	−6.8				3.5	1.6	E		
	1515	0	18	18	18	4.3	1.9	E		
4 Mar	0830	−14.0/−13.0	18	16	14			E	25	
	1130	−8.4				2.1	0.9	E		
	1515	−5.0	18	18	17			E		
5 Mar	0835	−5.2	18	18	17			E		
	1230	−2.1				6.3	2.8	E		
	1530	+0.7	19	19	19	10.3	4.6	NE		
6 Mar	0830	−12.1	15	15	15			NE		
	1125	−7.1				2.7	1.2	S		
	1535	−6.4	16	16	15	2.1	0.9	W		

*Indicates missing data

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